Saskatchewan
Research Council

TRACK LOADING STUDY - STRAIN GAUGE TESTS

Phase One Report

for

Saskatchewan Highways and Transportation
Engineering Division
Transportation Systems Branch

by

Equipment & Machinery
Development Division

Technology Transfer and Business Development Branch

Publication I-4404-3-E-91

September, 1992

TRACK LOADING STUDY - STRAIN GAUGE TESTS

Phase One Report

for

Saskatchewan Highways and Transportation
Engineering Division
Transportation Systems Branch

by

Allan Malinoski and Joe Jones
Equipment and Machinery
Development Division

Technology Transfer and Business Development Branch

Saskatchewan Research Council
15 Innovation Boulevard
Saskatoon, Saskatchewan
S7N 2X8
Telephone: (306) 933-5459
Fax: (306) 933-7896

SRC Publication No.
I-4404-3-E-91
September, 1992

TABLE OF CONTENTS

		Page
EXECUTIVE SUMMARY		iii
1.0	INTRODUCTION	1
2.0	WORK STATEMENT	2
3.0	WORK PERFORMED	3
	3.1 Assessment and Preparation	3
	3.2 Rail Stress-Strain Relationships	5
	3.3 Equipment Installation	20
	3.4 Field Testing	27
	3.5 Test Results	28
4.0	CONCLUSIONS	34
5.0	RECOMMENDATIONS	36

	Appendix Page
APPENDIX A - Strain Measurement Instrumentation	1
APPENDIX B - Plan View, Strain Gauge Locations at Dummer, Saskatchewan	7
APPENDIX C - SNAPSHOT Data Analysis Software	15
APPENDIX D - Test Train Layout	23

EXECUTIVE SUMMARY

Many rail branch lines in Saskatchewan are in a deteriorated state. These unrehabilitated branch lines are typically rated at 177,000 pound load limit, which is less than a fully-loaded grain hopper car gross weight limit of 250,000 to 263,000 pounds.

As the grain boxcar fleet is retired in the near future, the hopper car will become the primary vehicle for the movement of grain. Maximum permitted weights on those lines that have not been fully upgraded will vary depending on rail weights and ground conditions, but by existing standards will still be less than the fully-loaded hopper car weight of 263,000 lbs. This will result in underloaded and underutilized equipment.

The railway branch lines of concern are of relatively light-density, low-volume and slow-speed. The consequences of a failure on one of these lines is substantially less than on a high-volume line involving the transport of people or dangerous goods. Therefore, a lower factor of safety can be tolerated when setting the maximum loading. As well, since subgrade strength varies throughout the year, it is reasonable to vary the maximum loading throughout the year.

To deal with these low-volume, low-speed branch lines, the Transportation System Branch of Saskatchewan Highways and Transportation has initiated a Track Loading Capability Study. This study is designed to determine the maximum safe loading throughout the season for slow-speed, low-volume branch lines with a view to maximizing car loadings and minimizing capital investment in upgrading. It is expected that this study will also identify track structure improvements that are cost effective.

In November, 1990, Saskatchewan Highways and Transportation, Transportation Systems Branch, invited the Saskatchewan Research Council (SRC) to participate in the Track Loading Capability Study. SRC's involvement was designed to supplement the work completed by Clifton Associates Ltd., 25 July 1990, File R971, Geotechnical Investigation Track Load Capacity Study, Avonlea Subdivision.

SRC carried out short-term strain gauge testing at Dummer, Saskatchewan, on Southern Rail's (SRCL) Avonlea south line.

Four test cross sections selected within a four-metre length of track at the test site were instrumented with weldable strain gauges at eight measurement points. At each of these points, four strain gauges were precisely positioned and attached to the rail.

The deformation (and strain gradient) produced in the rails by vertical loading from the four loaded grain hopper cars pulled by the road/rail vehicle caused a change in the voltage signal being measured at each of the eight points.

A high-speed PC computer-based data acquisition system installed in the on-site trailer measured the voltage signals from the eight strain gauge circuits and stored the values in converted form in disk files on a computer hard disk.

Special software (SNAPSHOT), running on the site computer, controlled the collection of the voltage signals from the eight measurement points and storage of the data in files on the PC hard disk. The software also provided options for viewing the collected data in graphical form on the monitor.

Analysis of the data collected during the field tests was carried out to produce corresponding values of strain. Values of vertical bending stress occurring in the rails were determined from the strain values using Hooke's Law, which describes the linear relationship between stress and strain.

Average calculated vertical bending stresses from tests carried out on March 21, 1991, at Dummer, Saskatchewan at speeds of 8, 16, 25 and 30 km/hr vary from 23 to 24 KSI. Momentary maximum vertical bending stresses vary from 30 to 37 KSI (1 KSI = 1000 psi).

What is the significance of these stress values compared to the capacity of the rail?

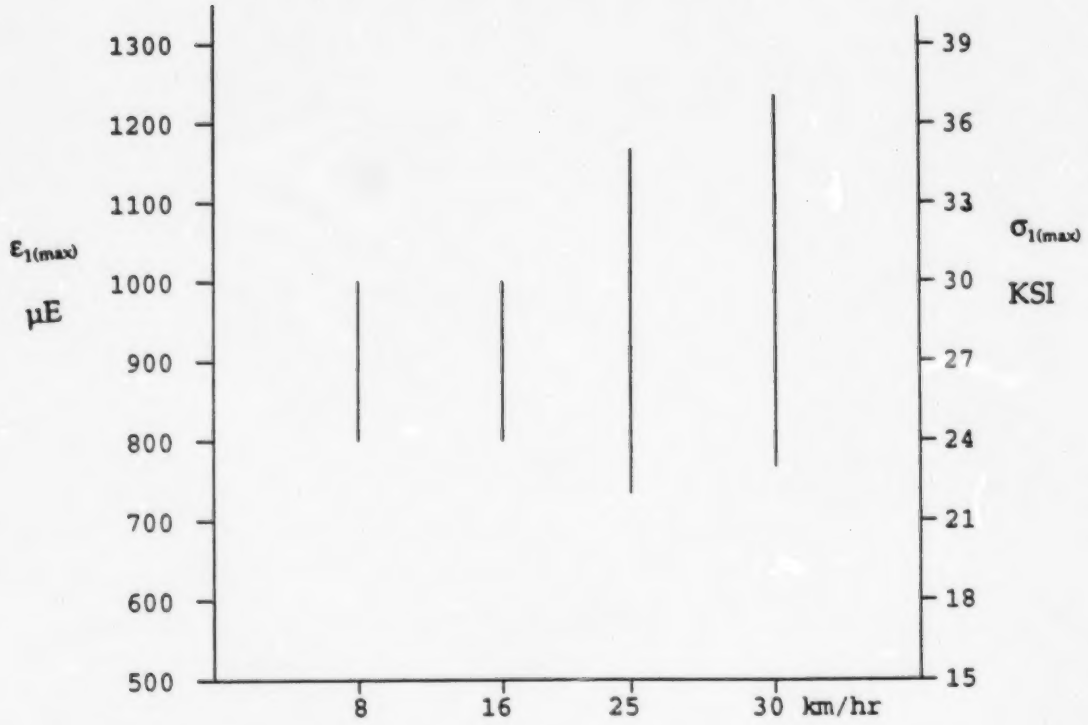
If a designer is sizing a new track installation, the American Railroad Engineering Association (AREA) suggests the following reductions:

- 7,000 psi (pounds per square inch) reduction in jointed rail to allow for temperature stresses.
- Lateral bending, 20% reduction
- Rail wear and corrosion, 15% reduction
- Unbalanced superelevation, 25% reduction
- Track conditions, 25% reduction

A generally-accepted value for the yield point of rail steel is 70,000 psi. A rail designer using AREA recommendations would use 32,000 psi when calculating a design value for allowable static axle loading. The actual operating stress in the rail could be higher than 32,000 psi, depending upon which of the various factors previously mentioned are acutally occurring. If all of the previously mentioned factors are combined, then the actual operating stress could approach 70,000 psi.

Note that in our testing, we measured actual vertical bending stress values between 23,000 psi to 37,000 psi, substantially below 70,000 psi. The following figure graphically illustrates the data.

Range of Maximum Bending Strains[1] and Stresses[2]
For Hopper Car[3] Speeds of 8, 16, 25 and 30 km/hr
Dummer, Saskatchewan Tests - March 21, 1991



	8 km/hr		16 km/hr		25 km/hr		30 km/hr	
	ε_1	σ_1	ε_1	σ_1	ε_1	σ_1	ε_1	σ_1
High	1006	30.2	999	30.0	1174	35.2	1234	37.0
Low	795	23.9	784	23.5	718	21.5	773	23.2
Average	901	27.0	892	26.8	946	28.4	1004	30.1

1. See Note 4, Page 31
2. See Note 6, Page 31
3. See Appendix D - Test Train Layout

1.0 INTRODUCTION

The federal government has invested over $1 billion in prairie branch line rehabilitation over the last ten years. Track specifications were established by CNR and CPR for qualifying branch lines. Termination of the rehabilitation program in 1989 has left many miles of branch lines in a deteriorated state resulting in reduced speeds and/or maximum loads. In addition, the existing standard of many of the rehabilitated branch lines was typically a 177,000 pound load limit, which is less than a fully-loaded grain hopper car gross weight limit of 263,000 pounds.

As the grain boxcar fleet is retired in the near future, the hopper car will become the primary vehicle for the movement of grain. Maximum permitted weights on those lines that have not been fully upgraded will vary depending on rail weights and ground conditions, but by existing standards will still be less than the fully-loaded hopper car weight of 263,000 pounds. This will result in underloaded and underutilized equipment.

The railway lines of concern are relatively light-density, low-volume, slow-speed branch lines. The consequences of a failure on one of these lines is substantially less than on a high volume line involving the transport of people or dangerous goods. Therefore, a lower factor of safety can be tolerated when setting the maximum loading. As well, since subgrade strength varies throughout the year it is reasonable to vary the maximum loading throughout the year.

To deal with these low-volume, low-speed branch lines, the Transportation System Branch of Saskatchewan Highways and Transportation has initiated development of a 'road-railer' vehicle. The design objective is to produce a vehicle light enough to operate on the highway and yet develop enough traction on rails to move up to eight grain hopper cars.

In conjunction with development of the 'road-railer' vehicle, in the autumn of 1989, the Southern Rails Cooperative Ltd. (SRC) was formed to begin a road/rail operation under an operating authority from the Province on the Avonlea Subdivision, previously owned and operated by Canadian National Railways. This line had been designated a grain-dependent branch line, serving country elevator stations at Parry and Truax. During the Branch Line Inquiry conducted by the Railway Transport Committee, Canadian Transport Commission, in 1984, it was the submission of the Province of Saskatchewan that this type of project be undertaken as an alternative to branch line abandonment or to traditional short-line railway operations. In presenting this option, the Province was seeking to

contribute to the continuation and improvement of Prairie branch line services and to the movement of grain by rail at reduced system costs, recognizing the cost impacts on all participants.

The Southern Rails Cooperative road/rail short line utilizes the prototype 'road-railer' vehicle developed by Saskatchewan Highways and Transportation, namely a single modified high-rail highway tractor capable of serving a number of separate branch lines. The operation involves loading of rail cars at country elevators and delivery of cars to the main line carrier at an interchange point. The road/rail power unit travels between elevator points as a railway unit over retained railway lines, and moves between branch lines as a highway unit. The road/rail power unit presents an application of new technology utilized in an innovative, practical manner.

The Province of Saskatchewan has provided assistance to the Southern Rails Cooperative in establishment of this demonstration project. This assistance includes specifications pertaining to an evaluation of the project for a period of three years.

In addition to providing assistance to the Southern Rails Cooperative Ltd. in establishment of a demonstration project, Saskatchewan Highways and Transportation has initiated a Track Loading Capability Study.

In conjunction with the road/road project, this study is designed to determine the maximum safe loading throughout the season for slow-speed, low-volume branch lines with a view to maximizing car loadings and minimizing capital investment in upgrading. It is expected that this study will also identify track structure improvements that are cost effective.

2.0 WORK STATEMENT

In November, 1990, Saskatchewan Highways and Transportation, Transportation Systems Branch, invited the Saskatchewan Research Council to participate in the Track Loading Capability Study. Involvement was to include the following:

Phase One Short-term strain gauge testing at Dummer on Southern Rails' (SRCL) Avonlea South line, ANALYSIS OF RESULTS and REPORT on track loading capability;

Phase Two Long-term strain gauge testing, ANALYSIS OF RESULTS and REPORT;

Phase Three DEVELOPMENT of Track Finite Element analytical model, DEMONSTRATION loading runs, and REPORT.

Phase One is now complete. This report presents a description of tasks performed including analysis of results, conclusions and recommendations. A Preliminary Report was issued in April, 1991, and an interim Summary Report was issued in July, 1991.

As of November, 1991, Phase Two is in progress, Phase Three has not yet begun.

In Phase One, the Saskatchewan Research Council conducted short term strain gauge testing on Southern Rails Cooperative Ltd.'s Avonlea South Line at Dummer, Saskatchewan, for Saskatchewan Highways and Transportation.

The Saskatchewan Research Council's primary tasks in this phase were:

1. Assess the strain gauge instrumentation requirements in order to acquire strain data during field tests at Dummer.

2. Recommend, purchase and verify the operation of suitable strain gauge instrumentation for these field tests.

3. Install the above-mentioned instrumentation at the Dummer test site.

4. Conduct defined tests at the Dummer test site. Analyze the collected strain data to determine strain magnitudes and calculate resultant single plane bending stresses due to vertical loading.

The following section, 3.0 Work Performed, presents the results of the Phase One study.

3.0 WORK PERFORMED

3.1 Assessment and Preparation

During November and December, 1990, strain gauge instrumentation requirements for the project were assessed and recommendations were made

to Saskatchewan Highways and Transportation. The recommended system included:

1. A computer-based high-speed data acquisition system and software.
2. A signal conditioning assembly housed in an insulated enclosure.
3. Cabling assembly.
4. Weld-on strain gauges.

See Appendix A for further details.

Upon approval from Saskatchewan Highways and Transportation SRC purchased the required instrumentation.

Discussions were held with Saskatchewan Highways and Transportation personnel to discuss possible strain gauge configurations and positioning. Agreement was reached regarding the number of strain gauges (32) and cross sections (4) to be employed at the field test site. For each strain measurement point, four gauges would be used in a full bridge configuration to provide temperature and lateral bending strain compensation.

Positions 1, 2, 3, 4 represent strain gauges located on the web of the rail at eight locations.

60 lb/yd A.S.C.E. Rail
(Dummer, SK test site)

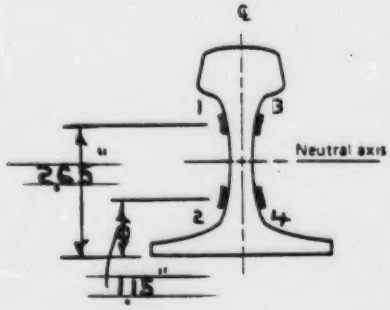


Figure 3.1-1

The instrumentation was set up and tested in late January and early February, 1991. A 5 foot, 85 lb/yard test rail section was instrumented with strain gauges, static loading tests were carried out on this section at the University of Saskatchewan, Civil Engineering Lab, to verify the system hardware and software performance prior to field installation.

3.2 Rail Stress-Strain Relationships

Railroad track rails experience loads resulting in the following types of stresses:

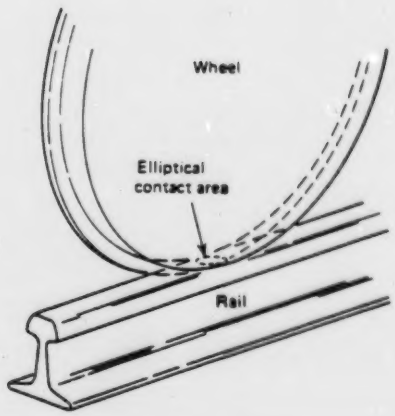


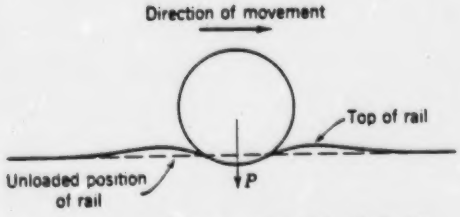
Figure 3.2-1

Bending stress (vertical)
The vertical component of wheel loads causing deflection.

Bending stress (lateral)
From lateral components of wheel loads, from hunting and nosing action, and from thermal forces and brake applications.

Shearing stress
From the vertical and lateral components of wheel loads damaging the metallic structure of the rail.

Longitudinal stress
Due to wave action under the passage of car wheels; also due to thermal forces.



Wave action in loaded rail.

Figure 3.2-2

Torsional or twisting stress
Due to the eccentricity of applied loads and to lateral flexibility; also due to the tendency of a rail to rotate about its points of lateral and longitudinal restraint.

Contact stress
A concentration of local shearing and bending stresses on the rail surface and immediately below the point of load application.

Moving trains produce dynamic impacts due to factors such as roll, slip, lurch, shock, buff, torque, load transfer, vibration and unequal distribution of live load.

No entirely adequate way is available to account for these dynamic effects. However, British Railway charts and American Railway Engineering Association procedures account for dynamic loading by the inclusion of speed factors in relation to static wheel loads.

Higdon, Ollsen, Stiles and Weese in Mechanics of Materials, 2nd Edition, discuss the concept of 'equivalent static load' for engineering applications where the velocities of applied dynamic loads are small enough to justify the assumption that the material behaves in the same manner as it does under slowly applied loads.

Using this assumption, an *equivalent static load* can be determined which will produce the same maximum deflection as that due to the dynamic load. This assumption implies that the stress-strain diagram (see Figure 3.2-11) for any point in the loaded system, as well as the strain distribution (see Figure 3.2-10), will be identical under either the *dynamic* or the *equivalent static* load.

As an analogy, consider the steel cantilever beam of Figure 3.2-3(a) on which the weight, *W*, is dropped as indicated. The variation of the end deflection of the beam with respect to time is shown in Figure 3.2-3(b) where Δ, equal to δ_{max}, is the maximum deflection resulting from the falling weight transferring part of its kinetic energy ($mv^2/2$) to the beam and where δ_{stat} is the static deflection resulting when the beam and weight finally reach equilibrium. The static load, *P*, applied as in Figure 3.2-3(c) produces the same maximum deflection, Δ; and the deflection curve and stress-strain diagrams are assumed to be the same in both cases.

In our rail loading situation, we can liken W to train static weight and P (which is greater than W) is by analogy equivalent to W plus additional (dynamic) load due to train speed. Thus in our rail loading situation, we have calculated maximum bending rail stresses due to momentary maximum deflection and corresponding maximum strains.

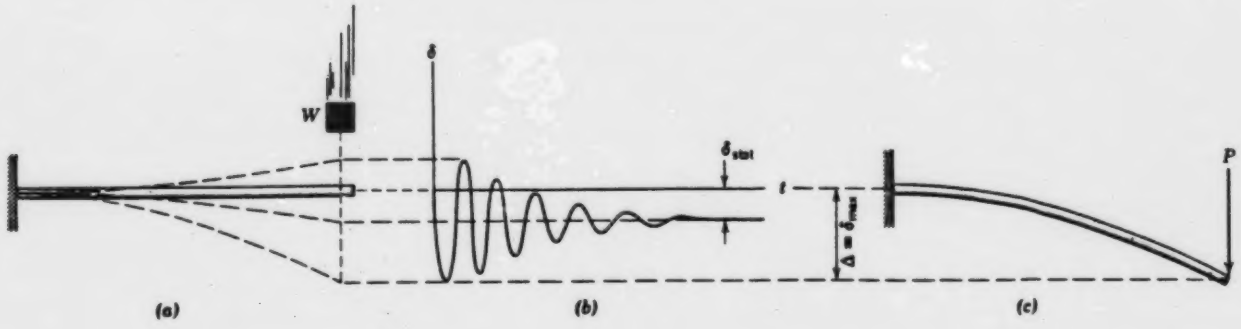
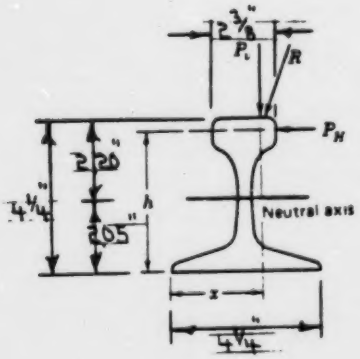


Figure 3.2-3

Dr. W. Hay in Railroad Engineering, 2nd Edition, Wiley - Interscience indicates that a rail can be sized by designing for elastic bending stress due to the vertical loading component, Pv.

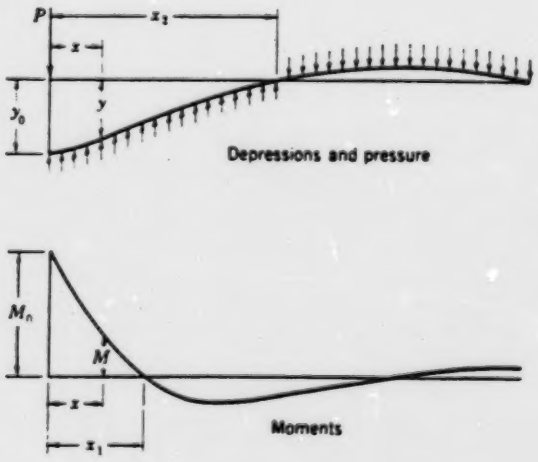


Strain Gauged Rails at Dummer, SK test site
60 lb. A.S.C.E.

Cross Sectioned Area = 5.93 in^2 (unworn)
Section Modulus (head) = 6.62 in^3
Section Modulus (base) = 7.10 in^3
Moment of Inertia = 14.56 in^4
A.S.C.E. lbs/yard (nominal) = 60.0

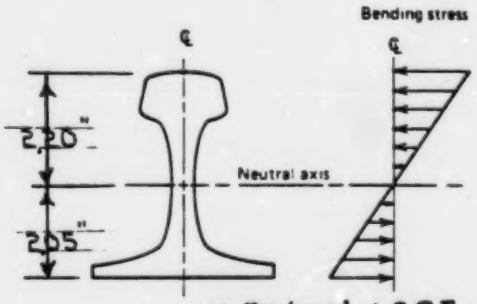
Overturning and Resistive Forces

Figure 3.2-4



Single-wheel load depression and bending moment distribution.

Figure 3.2-5



60 lbs/yard A.S.C.E. rail

$$\frac{I}{2.20} = \frac{14.56}{2.20} = 6.62\ in^3\ \textit{Section Modulus (head)}$$

$$\frac{I}{2.05} = \frac{14.56}{2.05} = 7.10\ in^3\ \textit{Section Modulus (base)}$$

Figure 3.2-6

A rail is considered as a continuously and elastically supported flexible beam deflecting under load, with the load distributed over 9-11 ties. The maximum deflection beneath a single wheel is obtained from the equation:

$$Y_o = -\frac{P_v}{(65EIu^3)^{1/4}} \qquad \ldots (1)$$

Where P_v = wheel load (static or adjusted for dynamic impact)
u = modulus of track elasticity in pounds per inch per inch
E = modulus of elasticity of rail steel = 30×10^6 psi
I = moment of inertia of the rail in inches to the fourth power

The moment of inertia (I), and the section modulus (S), determine the basic strength of the rail in bending.

The maximum bending moment is

$$M_o = P_v \left(\frac{EI}{64u}\right)^{1/4} = 0.318\ P_v x_1 \qquad \ldots (2)$$

where the distance to zero bending is

$$x_1 = \frac{\pi}{4}\left(\frac{4EI}{u}\right)^{1/4} \quad \ldots (3)$$

Knowing the bending moment, the maximum bending stress can be computed as

$$\sigma = \frac{M_o c}{I} \quad \ldots (4)$$

where σ is the bending stress in pounds per square inch, I is the moment of inertia of the rail, and c is the distance in inches from the base of rail to the neutral axis, or from the top of the rail to the neutral axis, whichever distance is larger.

$M_o c/I$, can be used to compute stress from a bending moment based on wheel load and the track stiffness modulus. Having an allowable stress, the maximum allowable bending moment and, from this, the maximum allowable wheel load and/or track stiffness modulus can be determined. There must therefore be an allowable maximum or working stress.

Standard carbon rail steel has a Brinell hardness of 250-278; high-strength steels may be higher, 321-388. The yield point of standard rail steel is about 70,000 psi and its modulus of elasticity is taken as 30×10^6 psi. Saskatchewan Highways and Transportation has indicated that 70 KSI yield rail steel is typical for prairie branch lines.

AREA regulations require reduction of 7,000 psi for temperature stresses in jointed rail; 20,000 psi for continuous welded rail. Additional allowances or factors of safety must be included. Among a variety of values, the AREA *Manual*, 1980-1981 revision, p. 22-3-15, suggests the following:

- Lateral bending 20%
- Rail wear and corrosion 15%

- Unbalanced superelevation 15%
- Track conditions 25%

The combined effect is $1.20 \times (1.15)^2 \times 1.25$, or 1.98. For jointed rail the allowable stress is

$$S_j = \frac{70{,}000 - 7{,}000}{1.98} = 31{,}818 \text{ psi} \qquad (\text{use } 32{,}000 \text{ psi})$$

. . . (5)

For CWR the allowable stress is

$$S_{CWR} = \frac{70{,}000 - 20{,}000}{1.98} = 25{,}253 \text{ psi} \qquad (\text{use } 25{,}000 \text{ psi})$$

. . . (6)

where S_j = allowable bending stress in jointed rail due to vertical loading
where S_{CWR} = allowable bending stress in welded rail due to vertical loading

So, by introducing safety factors to account for thermal stresses, lateral bending, unbalanced superelevation, curve wear, and track roughness, the theoretical yield point for rail steel is reduced from 70,000 to ~32,000 psi for jointed rail and ~25,000 psi for continuously welded rail.

At any given time, the types of stresses present in a rail (due to strains) can involve any and all of the previously mentioned vertical and lateral bending stresses, shearing stresses, longitudinal stresses, torsional stresses and contact stresses.

As our requirement for Phase One was to measure strain due to vertical loading only, a four strain gauge configuration below the top flange contact stress field was utilized at each of eight selected rail locations, as shown in the following figure. See Appendix B for plan view of the eight strain gauge locations at the Dummer, Saskatchewan site.

The full bridge arrangement of four strain gauges welded to the rail at each measurement point provided:

1) Temperature compensation

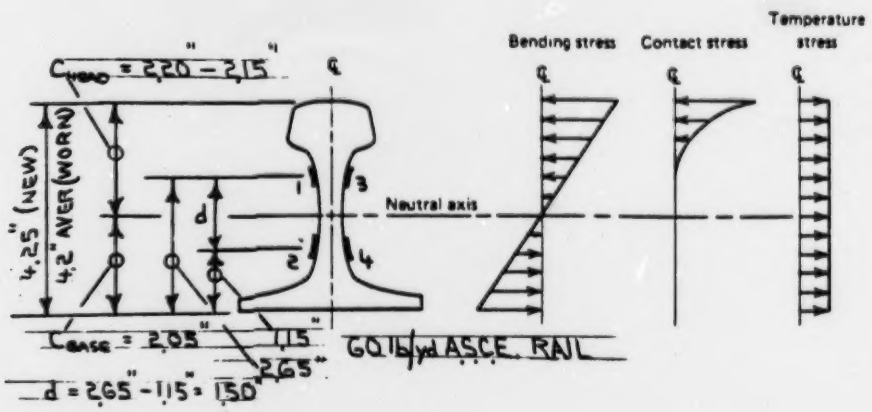
   A change in temperature of the rail has the same effect on all four gauges. The end result is that the voltage output signal of the bridge remains the same.

2) Axial tensile and compressive forces compensation

   In the presence of such forces, all four gauges experience the same elongation or shortening. The end result is that the voltage output signal of the bridge remains the same.

3) Lateral bending compensation

   During lateral bending, the two resistors on the same side of the rail web undergo the same strain. One side would be under compression and the other side under tension. Inspection of Wheatstone bridge relationships and the wiring arrangement used indicates that the voltage output signal of the bridge would not be significantly changed.



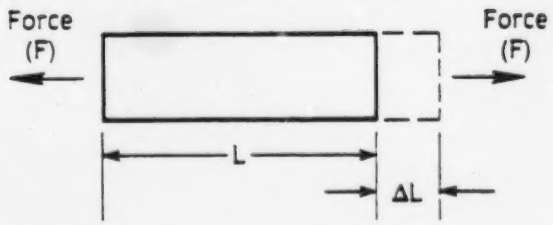
Strain gauge positions on rail.

Figure 3.2-7

In our data acquisition at the Dummer, SK site we made use of the known relationships between stress and strain in elastic metallic material. Strain gauge readings at the eight locations were noted when under load from the road-railer unit.

When a force is applied to an object, the object deforms. Deformation which is a change in length is known as linear strain and is defined by the following equation.

$$Strain\ (\epsilon) = \frac{\Delta L}{L} \qquad \ldots (7)$$



Uniaxial Force Applied

Figure 3.2-8

To maintain the physical significance of strain, it is often written with units of inch/inch. For most metals the strains measured in experimental work are typically less than 0.005000 inch/inch. Since practical strain values are so small, they are often expressed in micro-strain which is $\epsilon \times 10^6$ and has the symbol, $\mu\epsilon$. Still another way to express strain is as percent strain, which is $\epsilon \times 100$. For example: 0.005 inch/inch = 5000 $\mu\epsilon$ = 0.5%.

Strain may be either tensile (positive) or compressive (negative). In a laboratory situation, when a rail is partially supported with the supports near the ends of the rail and a force is applied transversely to the rail between the supports, bending moments are set up along the length of the rail as shown in the following figure. These bending moments change from zero at the supports to a maximum value PL/4 at the centre.

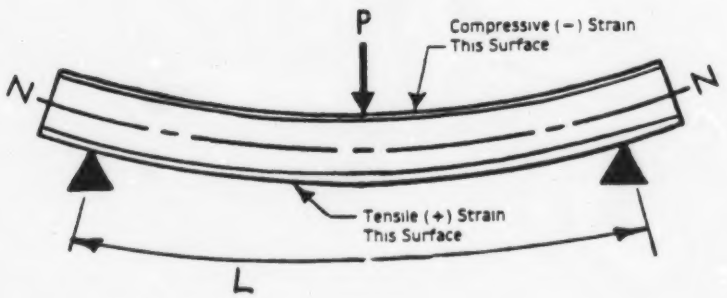
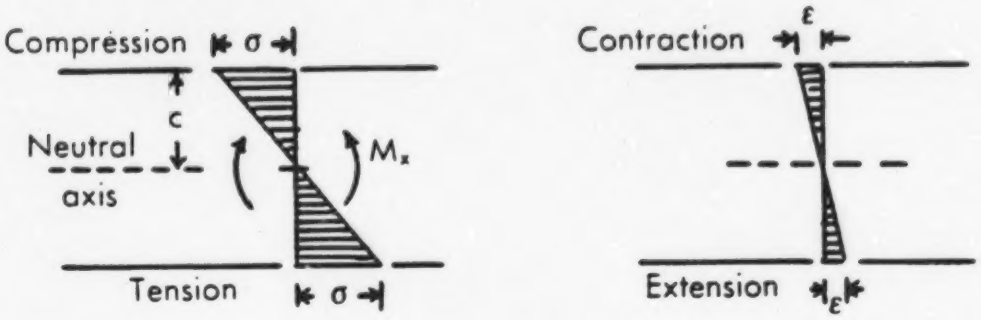


Figure 3.2-9

These bending moments set up bending stresses across all sections of the rail. The bending stress is zero at the neutral axis and increases linearly to a maximum at the outer fibers as the following figure shows. The top surface of the rail will be under compression and the bottom surface under tension. For elastic deformation, the distribution of strain in the rail will be similar to the stress distribution.

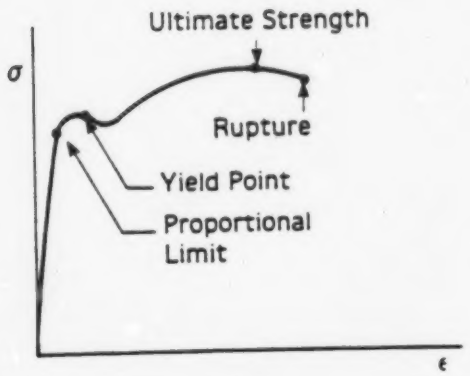


(a) Bending Stress

(b) Strain

Figure 3.2-10

Elastic bending stresses due to elastic strains in carbon steels can be shown on a stress-strain diagram as follows:



σ = bending stress

ϵ = strain

Stress-Strain Diagram for Steel

Figure 3.2-11

From the figure we can see that up to a point, called the proportional limit, there is a linear relationship between stress and strain. Hooke's Law describes this relationship. The slope of this straight line portion of the stress-strain diagram is the MODULUS OF ELASTICITY or YOUNG'S MODULUS for the material. The modulus of elasticity, E, has the same units as stress (force per unit area) and is determined experimentally for materials. Written in equation form this stress-strain relationship is

$$\sigma = E \cdot \epsilon \qquad \ldots (8)$$

Stress cannot be directly measured, however, because of the above relationship stress can be calculated from strain.

The tensile and compressive strains due to bending occurring at any section of the beam can be measured with strain gauges arranged in a full bridge or half-bridge configuration.

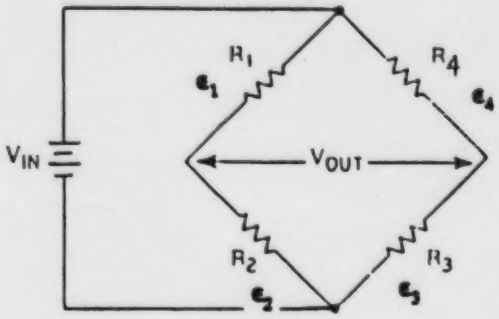
Bonded electrical resistance strain gauges are commonly used to measure normal strain where there is a fractional change in length of an object. The electrical resistance strain gauge consists of a conductor placed in a grid on a carrier matrix. A change in length of the conductor causes a change in the resistance of the conductor. This property provides the basis of how a strain gauge is able to measure strain in an object. The measure of a strain gauge's resistance change with strain is called gauge factor, GF.

$$GF = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R/R}{\epsilon} \qquad \ldots (9)$$

Gauge factor is defined as the ratio of the fractional change in resistance to the fractional change in length (strain) along the axis of the gauge.

When a strain gauge is cemented or welded to an object, it becomes one with the object. If the object undergoes strain, the gauge is strained an equal amount and its resistance changes correspondingly.

The Wheatstone Bridge circuit shown in the following figure consisting of four resistances in a parallel-series arrangement can very accurately detect small changes in resistance of one or all of the resistances. This circuit is commonly used to detect the small changes in resistance of strain gauges due to variations in the applied strain. The resistance shown in each of the four bridge arms can represent a strain gauge.



The Wheatstone Bridge

Figure 3.2-12

If we consider the case where the resistance in each arm is identical, there is no potential difference across the indicator, i.e. the bridge is "balanced."

The voltage output of the bridge is based on the following relationship

$$V_{out} = V_{in}\left(\frac{R3}{R3 + R4} - \frac{R2}{R1 + R2}\right)$$

. . . (10)

For unbalanced bridge measurements, it is necessary to measure the voltage output of the bridge in the unstrained and strained conditions.

The relationship for unbalanced bridge measurements is

$$V_r = \left[\left(\frac{V_{out}}{V_{in}}\right)_{strained} - \left(\frac{V_{out}}{V_{in}}\right)_{unstrained}\right] \quad \ldots (11)$$

If we consider the two previous equations and the relationship between strain and the change in resistance of strain gauges, the unbalanced voltage can be related to strain as follows:

$$V_r = \frac{GF}{4}(\epsilon_2 + \epsilon_4 - \epsilon_1 - \epsilon_3) \quad \ldots (12)$$

for R1 = R2 = R3 = R4 = R

A strain gradient in the vertical direction for a rail undergoing bending can be calculated using the relationship

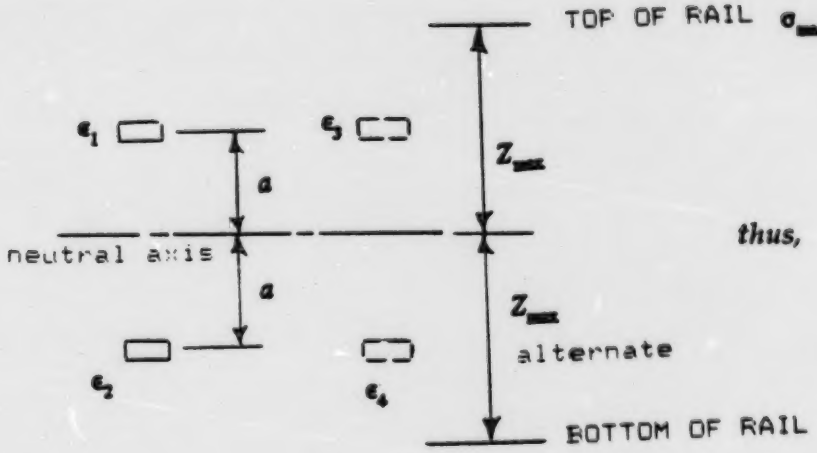
$$strain\ gradient = \frac{2 . V_r}{GF . d} \quad \ldots (13)$$

where d = the vertical distance separating the upper gauges (1 and 3) from the lower gauges (2 and 4) - see Figure 3.2-7.

This in turn allows development of two relationships for bending strain as follows

$$\epsilon_{max} @ Z_{max} location = \frac{V_r \cdot Z_{max}}{GF \cdot a} \quad \ldots (14)$$

$$\text{TOP OF RAIL} \quad \sigma_{max} @ Z_{max} location = E \cdot \epsilon_{max} \quad \ldots (15)$$



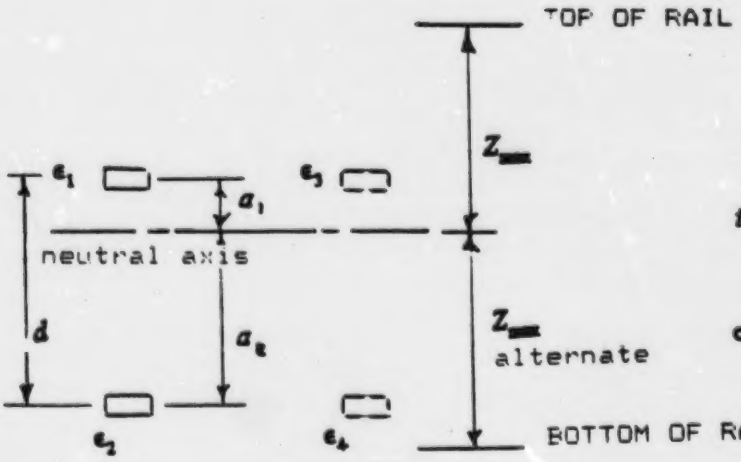
thus,

$$\sigma_{max} @ Z_{max} = E \left[\frac{V_r \cdot Z_{max}}{GF \cdot d} \right] \quad \ldots (16)$$

Symmetric Placement of Strain Gauges
about Neutral Axis

Figure 3.2-13

$$\epsilon_{max} @ Z_{max} location = \frac{2V_r \cdot Z_{max}}{GF \cdot d} \quad \ldots (17)$$



$$\sigma_{max} @ Z_{max} location = E \cdot \epsilon_{max} \quad \ldots (18)$$

thus,

$$\sigma_{max} @ Z_{max} location = E\left[\frac{2V_r \cdot Z_{max}}{GF \cdot d}\right] \quad \ldots (19)$$

Nonsymmetric Placement of Strain Gauges about Neutral Axis

Figure 3.2-14

Again, note that d is the distance separating the upper gauges (1 and 3) and the lower gauges (2 and 4).

Z_{max} is the distance from the neutral axis to the outer fibres, either top or bottom of the rail.

3.3 Equipment Installation

During the first 3 weeks of March, 1991, the instrumentation was installed at the test site at Dummer, Saskatchewan.

Installation of the strain gauges on the rails first involved cleaning the rail webs with a power grinder and then an emery cloth at the selected locations. Strain gauges were then welded to the rail with a low-wattage welder.

The rail on the Avonlea South Line at Dummer is ALGOMA 60 lb/yard rail and has a worn height of ~4.2 inches (106.7 mm). At each of eight strain measurement points two pairs of opposing strain gauges were attached to both sides of the rail web, 1.15 inches (29.21 mm) and 2.65 inches (67.31 mm), respectively, above the bottom of the rail base. This strain gauge arrangement measures the strain gradient in the selected rail sections due to bending caused by vertical loading only.

The strain measurement system installed at the Dummer field test site consists of the following main components:

1. Computer: Data Train 386 25 MHZ.
2. Data Acquisition Board: Analog Devices RTI-860.
3. Signal Conditioning I/O Subsystem-Analog Devices: 3B series.
4. Strain gauges: Hi-Tec No. HBW-35-125-6-10GP.

The system is a relatively high speed measurement device capable of performing thousands of measurements per second on each channel. "SNAPSHOT" software loaded in the DataTrain 386 PC directs measurement taking with the data acquisition board. Data is displayed as graphical output on the monitor or stored as data files on the computer hard disk.

The four strain gauges installed on the rails for each measurement point are connected together in a full-bridge wheatstone bridge circuit. Changes in the bending strain gradient in the rails cause changes in the resistance of the strain gauges in each bridge. The changes in the resistances in each bridge cause corresponding changes in the voltage output of the bridges. By taking initial voltage measurements of each bridge in the unstrained state before the passage of the rail cars and also during the passage of the rails cars during a test, voltage differences can be calculated which can then be converted into strain gradient values. Because of the dynamic nature of the rail car wheel movements along the track, it is necessary to take successive measurements at a relatively fast rate in order to capture all strain events.

The following equations show the relationships between strain, bridge voltage output, signal voltage, and related parameters. Some equations are repeated for

convenience of discussion. Equations 11, 2, 5, 6, and 7 are used to calculate strain gradient and maximum bending strain from computer voltage signal measurements.

$$V_{out} = V_{in}\left(\frac{R3}{R3 + R4} - \frac{R2}{R1 + R2}\right)$$

(repeated) . . . (10)

Where V_{out} is the bridge output voltage
V_{in} is the bridge excitation voltage
R1, R2, R3, and R4 are the strain gauge resistances

$$V_r = \left[\left(\frac{V_{out}}{V_{in}}\right)_{strained} - \left(\frac{V_{out}}{V_{in}}\right)_{unstrained}\right]$$

(repeated) . . . (11)

Where V_r = the difference of the bridge voltage ratios between unstrained and strained conditions for unbalanced bridge strain measurements

$$GF = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R/R}{\epsilon}$$

(repeated) . . . (9)

Where GF = gauge factor is the measure of strain gauge change in resistance relative to its change in strain
R = strain gauge resistance
L = length of strain gauge

$$V_r = \frac{GF}{4}(\varepsilon_2 + \varepsilon_4 - \varepsilon_1 - \varepsilon_3)$$

(repeated) . . . (12)

Where ε_1, ε_2, ε_3, and ε_4 are the four strains measured in the wheatstone bridge circuit.

$$\textit{strain gradient} = \frac{2 \cdot V_r}{GF \cdot d}$$

(repeated) . . . (13)

Where d = the vertical distance separating the upper gauges (1 & 3) from the lower gauges (2 & 4)

$$\varepsilon_{max} = \frac{2V_r \cdot Z_{max}}{GF \cdot d}$$

(repeated) . . . (17)

Where ε_{max} = maximum strain at the outer fibre of the rail
Z_{max} = the distance from the neutral axis to the outer fibre

$$V_{out} = 0.002\ (V_s) - 0.01$$

. . . (20)

Where V_{out} = the bridge output voltage
V_s = the voltage signal measured by the computer and the data acquisition board

This equation converts the voltage signals measured into actual bridge output voltages.

The signal conditioning I/O subsystem operates independently of the computer and data acquisition board. The signal conditioning I/O subsystem includes eight individual conditioning modules for the eight channels being measured. Each module provides voltage excitation to the wheatstone bridge circuit containing the four strain gauges. Each module also amplifies the bridge signal and converts it from voltage form to current form for transmission to the data acquisition board. Each module can measure signals with frequencies up to 20,000 cycles per second.

The operation of the I/O modules is as follows:

Each module provides a bridge excitation voltage equal to 3.4 volts. The voltage of each bridge is constantly measured by the input of the module. The input signal from the bridge is amplified by a gain of 1,000 which provides a signal range of -10 to +10 volts DC. This signal is then converted to a current signal with the range 0-20 mA.

The current signal from each module is carried in individual current loops to a screw terminal input board external to the computer in the on-site trailer. A 500 ohm resistor in each current loop converts the 0-20 mA signal to a 0 to +10 volt signal. The signal input range of the data acquisition board is 0-10 volts.

The following table shows the relationship between the various signal ranges:

Wheatstone bridge voltage signal range	Module gain of 1,000	Module current signal range	Data acquisition board signal input range
+0.010 V	+10.0 V	20 mA	+10 V
0 V	0 V	10 mA	+5 V
-0.010 V	-10.0 V	0 mA	0 V

The data acquisition board is capable of measuring up to 200,000 readings per second. For 8 channels about 25,000 measurements per second could be taken for each channel. Several factors determine the actual throughput rate. Based on an evaluation of rail car wheel diameters, travel speeds and wheel-rail contact

area, under most conditions 1,000 to 2,000 measurements per second on each channel are the minimally-suitable sampling speeds for this study.

If, for example, the system is set to measure 1,000 measurements per second, the following series of events take place in one measurement cycle of 1/1,000 sec for each channel. Let us assume a bridge output voltage of +0.005 for the strained condition due to a vertical wheel load over the strain gauged point. Let us also assume a balanced bridge condition of 0 volts output for the unstrained condition.

The signal conditioning module senses the bridge output voltage of +0.005 volts and amplifies this signal to +5.0 volts. The module further modifies this +5.0 volt signal to 15 mA. The 500 ohm resistor in the current loop from the module to the screw terminal connector board converts the 15 mA signal to +7.5 volts. The data acquisition board inputs the +7.5 volt signal from the terminal connector board and converts it to digital form for handling by the computer. The computer outputs the signal value as +7.5 volts.

Now we can use the earlier mentioned equations to convert this signal back to an actual strain value.

First, using Equation 20

$$V_{out} = 0.002\ (V_s) - 0.01$$

V_s = +7.5 volts
V_{out} = 0.002 (+7.5) - 0.01
V_{out} = +0.005 volts

Second, using Equation 11

$$V_r = \left[\left(\frac{V_{out}}{V_{in}}\right)_{strained} - \left(\frac{V_{out}}{V_{in}}\right)_{unstrained}\right]$$

$$V_r = \frac{0.005}{3.4} - \frac{0}{3.4} = 0.00147$$

Third, using Equation 13

$$strain\ gradient = \frac{2.V_r}{GF.d}$$

Where d = 1.5 inches
GF = 2.05
V_r = 0.00147

$$Strain\ gradient = \frac{2\ (0.00147)}{2.05\ (1.5)} = 9.56\ x\ 10^{-4}\ in/in/in$$

Fourth, using Equation 17 in combination with Equation 13

$$\epsilon_{max} = \frac{2V_r \cdot Z_{max}}{GF \cdot d} = \left(\frac{2V_r}{GF \cdot d}\right) Z_{max}$$

Where Z_{max} = 2.05"
ϵ_{max} = $(9.56 \times 10^{-4})(2.05)$
= 1.9598×10^{-3}
= 1960 $\mu\epsilon$

Values of bending stress were determined from values of vertical bending strain by the relationship

$$\sigma_{max} = E \cdot \epsilon_{max}$$

(repeated) . . . (8)

Where σ_{max} = maximum stress
E = modulus of elasticity
ϵ_{max} =maximum strain

For steels, $\in = 30 \times 10^6$ psi. So, in our example

$$\sigma = (30 \times 10^6)(1.9598 \times 10^{-3})$$
$$= 58{,}794 \text{ psi}$$
$$= 58.8 \text{ KSI}$$

The strain gauge signal conditioning assembly is housed in an insulated enclosure located approximately 6 feet from the rails. Cables from the strain gauges are routed through flexible conduit to the signal conditioning enclosure. Signal and power cables from the on-site trailer to the enclosure are also routed through flexible conduit. The computer with the data acquisition board is located in the trailer.

3.4 Field Testing

Upon completion of the instrument installation, dynamic and static tests were performed with the Road/Railer and four loaded hopper cars on March 21, 1991.

The dynamic test conditions were as follows:

Test speeds:	8, 16, 25 and 30 km/hr
Test Weights:	Front 2 hopper cars loaded to 263,000 lbs
	Rear 2 hopper cars loaded to 220,000 lbs
Tests:	One pass at each speed

Four static axle load tests were also performed.

The raw data was collected and stored in amplified voltage units.

Upon completion of the tests the computer was taken back to SRC for use in the data analysis.

The data collected during the field tests at Dummer were analyzed to determine strain values.

Data analysis involved converting the raw data into strain units and calculating bending stresses from the strain values.

3.5 Test Results

The range of maximum microstrains and bending stresses obtained from the eight strain channels for four different speeds are shown in the following table:

Range of Maximum Bending Strains and Stresses		
Speed (km/hr)	Strain (microstrain)	Stress (KSI)
30 (Test 1)	215 - 1234	6.5 - 37.0
25 (Test 2)	210 - 1174	6.3 - 35.2
16 (Test 3)	241 - 1053	7.2 - 31.6
8 (Test 4)	245 - 1006	7.4 - 30.2

Immediately following are most detailed data summaries of Test 1, Test 2, Test 3 and Test 4. Section 4.0 Conclusions, discussed the significance of these test results.

Test 1 **File: 032/1010.PRN**
30 km/hr

Channel		0	1	2	3	4	5	6	7
V_s unstrained	1	5.8341	4.8617	4.9972	5.4797	6.3424	5.6358	4.1310	4.9152
$V_{s1(max)}$ strained	2	6.7529	5.6934	6.2012	6.5576	7.4170	6.9336	5.1904	6.3818
$V_{s2(max)}$ strained	3	5.1904	4.4873	4.5459	5.2246	5.7764	5.2051	3.6377	4.5459
$\epsilon_{1(max)}$ με	4	773	700	1013	907	904	1092	892	1234
$\epsilon_{2(max)}$ με	5	542	315	380	215	476	363	415	311
$\sigma_{1(max)}$ KSI	6	23.2	21.0	30.4	27.2	27.1	32.8	26.8	37.0
$\sigma_{2(max)}$ KSI	7	16.3	9.5	11.4	6.5	14.3	10.9	12.5	9.3

- Test 1 - 15 seconds duration
  - sampling rate at 5000 voltage readings per second per channel
  - total voltage readings = 15 x 5000 x 8 = 600,000
- For footnote references 1 to 7, see NOTES page following

Test 2 **File: 03211028.PRN**
25 km/hr

Channel		0	1	2	3	4	5	6	7
V_s unstrained	1	5.8164	4.8569	4.9896	5.4741	6.3287	5.6323	4.1261	4.9139
$V_{s1(max)}$ strained	2	6.6699	5.7080	6.1719	6.5771	7.4268	6.8555	5.2246	6.3086
$V_{s2(max)}$ strained	3	5.1660	4.4824	4.5410	5.2246	5.7861	5.2148	3.6133	4.5459
$\epsilon_{1(max)}$ με	4	718	716	995	928	924	1030	924	1174
$\epsilon_{2(max)}$ με	5	547	315	378	210	457	351	432	310
$\sigma_{1(max)}$ KSI	6	21.5	21.5	29.9	27.8	27.7	30.9	27.7	35.2
$\sigma_{2(max)}$ KSI	7	16.4	9.5	11.3	6.3	13.7	10.5	13.0	9.3

- Test 2 - 15 seconds duration
  - sampling rate at 5000 voltage readings per second per channel
  - total voltage readings = 15 x 5000 x 8 = 600,000
- For footnote references 1 to 7, see NOTES page following

Test 3 **File: 03211048.PRN**
16 km/hr

Channel		0	1	2	3	4	5	6	7
V_s unstrained	1	5.8165	4.8681	4.9938	5.4763	6.3253	5.6303	4.1347	4.9211
$V_{s1(max)}$ strained	2	6.7480	5.8301	6.1230	6.6016	7.4658	6.7627	5.3857	6.1084
$V_{s2(max)}$ strained	3	5.1904	4.4336	4.5313	5.1904	5.7959	5.1953	3.6523	4.5264
$\epsilon_{1(max)}$ με	4	784	810	950	947	960	953	1053	999
$\epsilon_{2(max)}$ με	5	527	366	389	241	446	366	406	332
$\sigma_{1(max)}$ KSI	6	23.5	24.3	28.5	28.4	28.8	28.6	31.6	30.0
$\sigma_{2(max)}$ KSI	7	15.8	11.0	11.7	7.2	13.4	11.0	12.2	10.0

- Test 3 - 22 seconds duration
  - sampling rate at 2976 voltage readings per second per channel
  - total voltage readings = 22 x 2976 x 8 = 523,776
- For footnote references 1 to 7, see NOTES page following

Test 4 **File: 03211116.PRN**
8 km/hr

Channel		0	1	2	3	4	5	6	7
V_s unstrained	1	5.8081	4.8685	4.9986	5.4761	6.3148	5.6278	4.1354	4.9229
$V_{s1(max)}$ strained	2	6.7529	5.7959	6.1670	6.6357	7.3584	6.7090	5.3027	6.1182
$V_{s2(max)}$ strained	3	5.1465	4.4189	4.5557	5.1855	5.7715	5.1904	3.6963	4.5459
$\epsilon_{1(max)}$ με	4	795	781	983	976	878	910	983	1006
$\epsilon_{2(max)}$ με	5	557	378	373	245	457	368	370	317
$\sigma_{1(max)}$ KSI	6	23.9	23.4	29.5	29.3	26.3	27.3	29.5	30.2
$\sigma_{2(max)}$ KSI	7	16.7	11.3	11.2	7.4	13.7	11.0	11.1	9.5

- Test 4 - 37 seconds duration
  - sampling rate at 1984 voltage readings per second per channel
  - total voltage readings = 37 x 1984 x 8 = 587,264
- For footnote references 1 to 7, see NOTES page following

NOTES (Test 1, Test 2, Test 3, Test 4)

1. V_s is the unstrained signal voltage measured by the data acquisition board, and streamed to the computer hard disc. Such signal voltages can be displayed on the video monitor screen through SNAPSHOP software. Appendix C illustrates how data can be displayed with SNAPSHOT software. Units are volts.

2. Tens of thousands of voltage readings relating to rail strain values were recorded during these test runs as the road/railer pulling four hopper cars moved by the strain gauged rail locations. Appendix D provides information relating to this test train assembly.

   Readings were taken for eight channels (0 - 7) corresponding to the eight strain gauge assembly locations, each consisting of four strain gauges connected in a wheatstone bridge configuration.

   V_{s1}(max) strained occurred when compressive strains at the top of the instrumented rails due to vertical loading were at a maximum, and correspondingly when tensile strains at the bottom of the rail due to vertical loading were at a maximum. This is the equivalent situation to static rail loading. Units are volts.

3. V_{s2}(max) strained occurred when tension strains at the top of the rail due to dynamic strain reversal were at a maximum, and correspondingly when compressive strains at the bottom of the rail due to dynamic strain reversal were at a maximum. Units are volts.

4. ε_1(max) are calculated microstrain values of compressive strain at the top of the rail due to vertical loading corresponding to the presence of V_{s1}(max) strained. Similar values can be calculated for microstrain values of tensile strain at the bottom of the rail at the same instant. However, because the distance from the rail neutral axis to outer fibres is greater to the top of the rail than to the bottom of the rail, only the larger magnitude of calculated microstrain is shown. Units are microstrain, $\mu\varepsilon$.

5. ε_2(max) are calculated microstrain values of tensile strain at the top of the rail due to dynamic strain reversal corresponding to the presence of V_{s2}(max) strained. Similar values can be calculated for microstrain values of compressive strain at the bottom of the rail at the same instant. However, because the distance from the rail neutral axis to outer fibres is greater to the top of the rail than to the bottom of the rail, only the larger magnitude of calculated microstrain is shown. Units are microstrain, $\mu\varepsilon$.

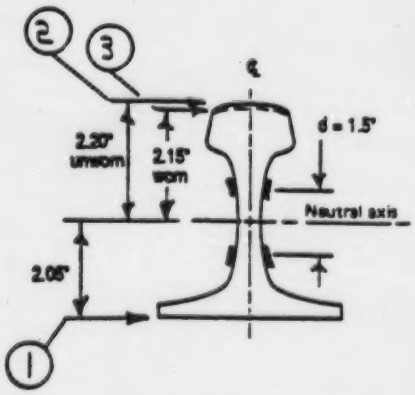
6. σ_1(max) is the calculated bending stress corresponding to ε_1(max). Units are Kips per square inch, KSI.

7. σ_2(max) is the calculated bending stress corresponding to ε_2(max). Units are Kips per square inch, KSI.

Example Calculation of $\varepsilon_{1(max)\mu\varepsilon}$ for Test 1, Channel 0

$$\epsilon_{1(max)} = \frac{2V_r \cdot Z_{max}}{GF \cdot d} = \frac{(2)(0.0005405)(2.20)}{(2.05)(1.5)} = 0.000773\ in/in = 773\ \mu\epsilon$$

Where Z_{max} = 2.20"[1]
GF (gauge factor for strain gauges) = 2.05
d = 1.5"



60 lb/yd ASCE rail

Figure 3.3-1

V_r = 0.0005405 volts, calculated from

$$V_r = \left[\left(\frac{V_{out}}{V_{in}}\right)_{strained} - \left(\frac{V_{out}}{V_{in}}\right)_{unstrained}\right] = \left[\frac{0.0035058}{3.4} - \frac{0.0016682}{3.4}\right] = 0.0005405\ volts$$

Where V_{in} = 3.4 volts (bridge exitation voltage)
$V_{out\ strained} = 0.002\ (V_{s1(max)strained}) - 0.01 = (0.002)(6.7529) - 0.01 = 0.0035058$
$V_{out\ unstrained} = 0.002\ (V_{s\ unstrained}) - 0.01 = (0.002)(5.8341) - 0.01 = 0.0016682$

Where $V_{s1(max)strained}$ = 6.7529 volts (from Test 1 data)
$V_{s\ unstrained}$ = 5.8341 volts (from Test 1 data)

1 unworn height used in calculations

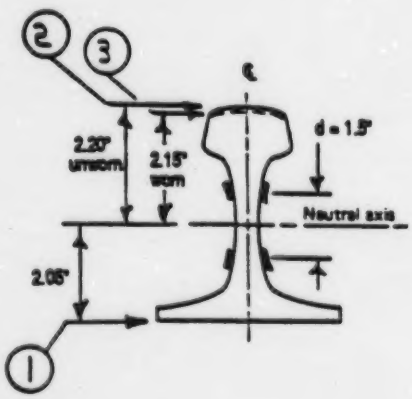
Example Calculation of $\varepsilon_{2(max)\mu\varepsilon}$, for Test 1, Channel 0

$$\epsilon_{1(max)} = \frac{2V_r \cdot Z_{max}}{GF \cdot d} = \frac{(2)(0.0003786)(2.20)}{(2.05)(1.5)} = 0.000542\ in/in = 542\ \mu\epsilon$$

Where Z_{max} = 2.20"

GF (gauge factor for strain gauges) = 2.05

d = 1.5"



60 lb/yd ASCE rail

Figure 3.3-2

V_r = 0.0003786 volts, calculated from

$$V_r = \left[\left(\frac{V_{out}}{V_{in}}\right)_{strained} - \left(\frac{V_{out}}{V_{in}}\right)_{unstrained}\right] = \left|\left[\frac{0.0003808}{3.4} - \frac{0.0016682}{3.4}\right]\right| = 0.0003786\ volts$$

Where V_{in} = 3.4 volts (bridge exitation voltage)

$V_{out\ strained} = 0.002\ (V_{s2(max)strained}) - 0.01 = (0.002)(5.1904) - 0.01 = 0.0003808$

$V_{out\ unstrained} = 0.002\ (V_{s\ unstrained}) - 0.01 = (0.002)(5.8341) - 0.01 = 0.0016682$

Where $V_{s2(max)strained}$ = 5.1904 volts (from Test 1 data)

$V_{s\ unstrained}$ = 5.8341 volts (from Test 1 data)

Example Calculation of $\sigma_{1(max)}$ KSI, for Test 1, Channel 0

$$\sigma = E \cdot \varepsilon = (30 \times 10^6)(0.000773) = 23190 \text{ psi} = 23.2 \text{ KSI}$$

Where σ = bending stress, KSI
E = modulus of elasticity for steel = 30×10^6 psi
ε = linear strain = $\varepsilon_{1(max)}$ = 773 $\mu\varepsilon$ = 0.000773 in/in

Example Calculation of $\sigma_{2(max)}$ KSI, for Test 1, Channel 0

$$\sigma = E \cdot \varepsilon = (30 \times 10^6)(0.000542) = 16260 \text{ psi} = 16.3 \text{ KSI}$$

Where σ = bending stress, KSI
E = modulus of elasticity for steel = 30×10^6 psi
ε = linear strain = $\varepsilon_{2(max)}$ = 542 $\mu\varepsilon$ = 0.000542 in/in

4.0 CONCLUSIONS

The strain measurement instrumentation performed as expected during the field tests. The initial data collected appears relatively consistent, and of reasonable magnitude, although somewhat higher as compared to GEOTRACK software vertical bending stress predictions as discussed in Clifton Associates Ltd. report "Geotechnical Investigation Track Load Capacity Study, Avonlea Subdivision," File R971, 25 July 1990.

The data analyzed in this report resulted from dynamic testing of the road/railer unit pulling four loaded hopper cars on March 21, 1991. The two front hopper cars were loaded to 263,000 lbs. The rear two hopper cars were loaded to 220,000 lbs. Tests were conducted at four speeds: 8, 16, 25 and 30 km/hour, with one pass at each speed. The rails were 60 lb/yd ASCE. The ties varied from 7" to 8" in width, and 22" to 24" on centers. Ground conditions during the test day

showed some surface thawing with resultant slippery and muddy conditions in the area of the rails adjacent to the test trailer.

Appendix B illustrates the Dummer, Saskatchewan test location of four instrumented railway cross sections each consisting of two individual rail cross sections, each of which has four of, strain gauges arranged in a Wheatstone Bridge configuration. An examination of Section 3.5 Test Results, shows that each of the eight individual rail cross sections are identified as channel locations 0 to 7. The data presented in this section illustrates the maximum voltage ranges recorded during the testing, with corresponding maximum strain, and maximum bending stress calculated values.

Values between channels do vary somewhat, with Channel 7 in almost all cases yielding the highest projected bending stresses due to vertical loading.

Test 1 at 30 km/hr: the maximum bending stress calculated = 37 KSI

Test 2 at 25 km/hr: the maximum bending stress calculated = 35.2 KSI

Note from Appendix B illustration of strain gauge locations at the Dummer, Saskatchewan test site, cross section 1 and cross section 3 are directly over rail ties, whereas cross section 2 and cross section 4 are between rail ties.

If we average the calculated maximum bending stresses for cross section 1 (channel 0 and channel 1) and cross section 3 (channel 4 and channel 5) for Test 1 at 30 km/hr, we have

$$(23.2 + 21.0 + 27.1 + 32.8)/4 = 26.0 \text{ KSI}$$

If we average the calculated maximum bending stresses for cross section 2 (channel 2 and Channel 3) and cross section 4 (channel 6 and channel 7) for Test 1 at 30 km/hr, we have

$$(30.4 + 27.2 + 26.8 + 37.0)/4 = 30.4 \text{ KSI}$$

If we average the calculated maximum bending stresses for cross section 1 (channel 0 and Channel 1) and cross section 3 (channel 4 and channel 5) for Test 2 at 25 km/hr, we have

$$(21.5 + 21.5 + 27.7 + 30.9)/4 = 25.4 \text{ KSI}$$

If we average the calculated maximum bending stresses for cross section 2 (channel 2 and Channel 3) and cross section 4 (channel 6 and channel 7) for Test 2 at 25 km/hr, we have

$$(29.9 + 27.8 + 27.7 + 35.2)/4 = 30.2 \text{ KSI}$$

Average values for Test 3 at 16 km/hr and for Test 4 at 8 km/hr have lower average values.

A generally-accepted value for the yield point of rail steel is 70,000 psi. A rail designer using AREA recommendations would use 32,000 psi when calculating a design value for allowable static axle loading. The actual operating stress is the rail could be higher than 32,000 psi, depending upon which of the various factors previously mentioned are actually occurring. If all of the previously-mentioned factors are combined, then the actual operating stress could approach 70,000 psi.

Note that in our dynamic testing we measured actual vertical bending stress values between 23,000 psi to 37,000 psi, substantially below 70,000 psi.

5.0 RECOMMENDATIONS

Ground conditions have a direct effect on rail stress values. Equation 2 (Page 9) in Section 3.2 Rail Stress-Strain Relationships indicates the mathematical relationship (idealized) between maximum rail bending moment and the modulus of track elasticity. Note that as the modulus of track elasticity increases, the maximum rail bending moment decreases, and correspondingly the maximum bending rail stresses decrease.

An examination of the general trends for track modulus elasticity as discussed in Clifton Associates Ltd. report "Geotechnical Investigation Track Load Capacity Study, Avonlea Subdivision," File R971, 25 July 1990, indicates that modulus values can vary over 3.3 to 1 when comparing soft clay versus frozen till, with frozen till having the larger modulus values.

The Section 4.0 - Conclusions data summary results from this Phase One Study are only representative of spring ground conditions. To obtain a balanced picture of yearly variation of rail operational stresses, rail strain data should be examined for all seasons.

If conclusions are to be drawn about rail bending stresses in relation to safety and longevity of rail performance, we recommend that data be obtained that is representative of the full range of soil temperatures and corresponding modulus values. This requires recording and analysis of all seasons yearly variation of rail operational strains with calculation of corresponding maximum bending stresses. This has been proposed previously to be Phase Two, as discussed in Section 2.0 Work Statement in this report.

Fatigue fracture has become the mode of failure for continuously-welded new rails subject to wheel loadings from high-capacity cars and unit trains. In contrast, the secondary track jointed rail lines being examined in the Saskatchewan Highways Track Loading Capability Study have generally been in use for decades, but at lower tonnage rates per year than the mainlines. Nevertheless, some of the rail examined showed noticeable surface wear, top flange edge wear and plastic flow. One explanation for this is that it is possible that some of the installed rail may have been previously used. However, with the proposed increases in rail loading levels, would it be worthwhile to examine the fatigue life considerations, wear life considerations and their interrelationship? AAR's "User's Guide and User's Manual for a Fatigue Life Analysis Program" provides detailed guidance in setting up a rail fatigue analysis program if such a course of action is deemed to be necessary by Saskatchewan Highways.

However, note that when operational rail stresses are within AREA recommendations, Dr. Hay in "Railroad Engineering" indicates that rail life is usually expressed in millions of gross tons carried. Joint and surface deterioration usually do not set in until after the passage of 100 million gross tons, although overall service life may extend to 500 million gross tons.

How can we relate these tonnages to our Track Loading Study? One example, Table 2 in the report "Saskatchewan Road/Rail Operation Project Evaluation" Interim Report, August 1991, on page 11 consists of an SRC Traffic Summary from August 1990 to January 1991. For Avonlea origin, the total tonnage shipped over this period is 14,151 tons. For estimation purposes, multiply by 2 for total tonnage per year, or 28,302 tons. Assuming that rail stresses were within AREA allowables, dividing this tonnage into 100 million gross tons suggests an

operational life of over several thousand years for new rail. In practical terms, however, other factors will limit rail life to far less than this. Nevertheless, based on this calculation, it is assuring to see that much more yearly tonnage could be safely accommodated and still leave a very large service life projection.

It would be useful to do a calculation for the existing rails to estimate total rail tonnage since installation of the track to a projection into the future when the service life of the rail is estimated to be complete. Comparing total tonnage calculated to the 100 million tonnage service life range will indicate if there is any problem. However, unless the carry tonnages are very high, it is unlikely that 100 million tons will be exceeded before the track is hundreds of years old.

Other factors that affect rail service life and operational safety besides tonnage are axle loads, speed, amount of curvature, gradient, subgrade support, ballast support, and standard maintenance. We recommend that a rail systems preventative maintenance program be designed and implemented for purposes of safety and to maximize rail system service life.

We recommend that consideration be given to development of a software parametric model of the track system that would allow safe loading and life prediction calculations for various combinations of circumstances such as varying ground conditions throughout the year, varying rail weights, track geometry, live load, speed, etc. Such a model would also be useful in predicting required maintenance. In August 1992 correspondence to Saskatchewan Highways, SRC made a preliminary proposal for such a development.

We have previously mentioned rail joints. What is the effect of rail joints on track safety and overall rail life? What is the effect of loose and incorrectly torqued bolts? We recommend that consideration be given to a study of the interrelationship of joint-bar action in track and track bolt tension.

APPENDIX A

STRAIN MEASUREMENT INSTRUMENTATION

The following is a list of the strain gauge measurement instrumentation purchased for use at the test site at Dummer, Saskatchewan on SRCL's Avonlea South Line.

1. Data Train RD-DPC-3325 Computer
   - 25 MHz 80386 microprocessor c/w
     - Raven RD-1464 color monitor
     - Optima 1024 VGA-SYNC enhanced video adapter
     - ST-1126A/C hard drive - 100 MB
     - 1.2 MB floppy drive
     - 1.44 MB floppy drive
     - IC-387/25 math coprocessor
     - UR-2400 SI modem
     - Logitech mouse

2. Analog Devices: RTI-860 analog-to-digital microcomputer bus data acquisition board, complete with

   - ribbon cable
   - STP-SP screw termination panel

3. Software

   - AD-AC1913-FIL SNAPSHOP STORAGE SCOPE for use with AD RTI-860 A-D board
   - AD-AC1911-ST SNAP STREAM
   - DISK OPTIMIZER - Hard disk optimizer

4. Analog Devices - 3B series signal conditioning I/O subsystem

   - 1 - AD-AC1330 Rack mount
   - 1 - AD-3B01 Backplane
   - 1 - AD-AC1307 Power Supply
   - 1 - AD-AC1340-D Power Cord
   - 8 - AD-3B18-00 Signal conditioner module
   - 8 - AD-AC1310 Calibration kits
   - 1 - AD-AC1324 Screw terminal board

5. Signal conditioner housing

   SRC-fabricated insulated steel enclosure with heater and cooling fan.

6. HI-TEC standard single element weldable strain gauge

   - 46 of, Designation No. HBW-35-125-6-10GP
   - gauge resistance: 350 ± 1% Ω
   - gauge factor: 2.05 ± 1%

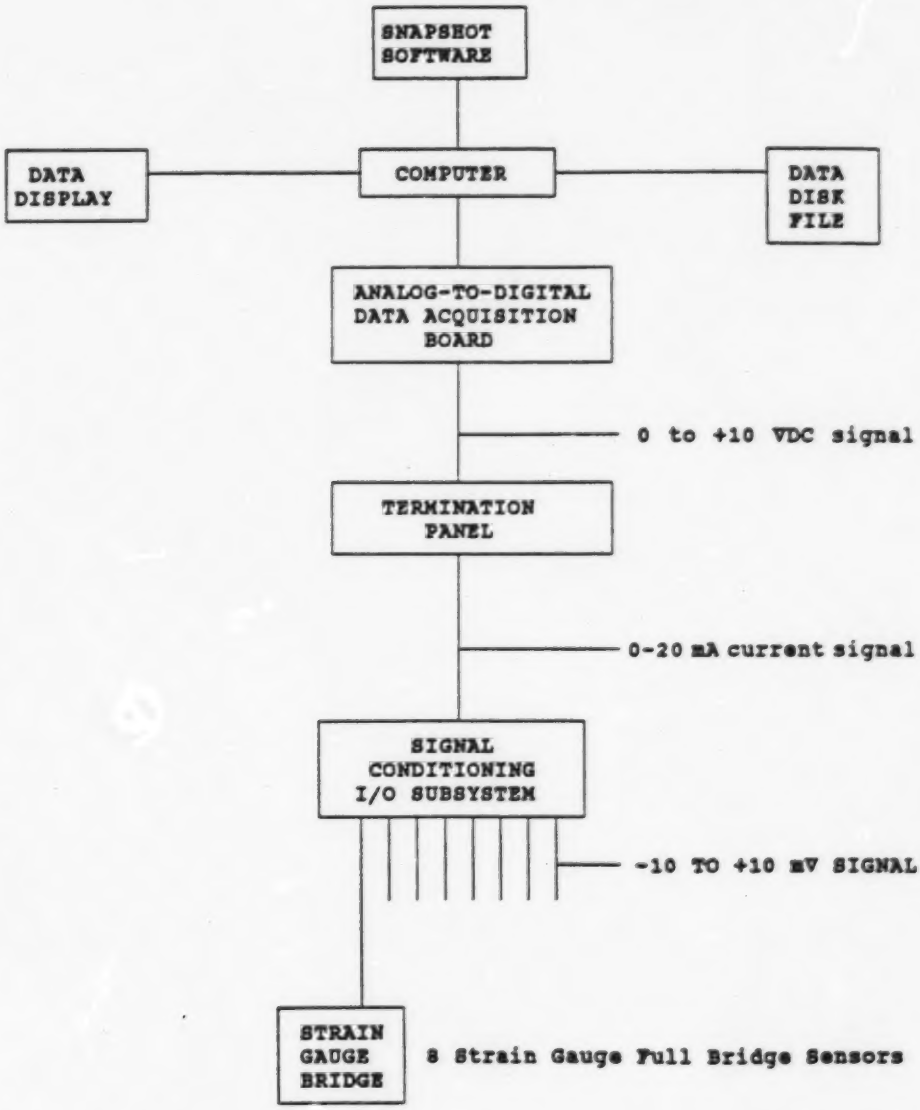
7. Signal cabling and conduit

   a) Strain gauge to signal conditioner
      - 2 pair #22 AWG shielded instrument cable
      - ½" liquid tight flexible conduit

   b) Signal conditioner to screw terminal board
      - 25 pair #22 AWG shielded instrument cable
      - ¾" liquid tight flexible conduit

8. Power cabling and conduit

   Trailer to signal conditioner housing
   - two #16 AWG-3 x 40′ power cord
   - 1" liquid tight flexible conduit

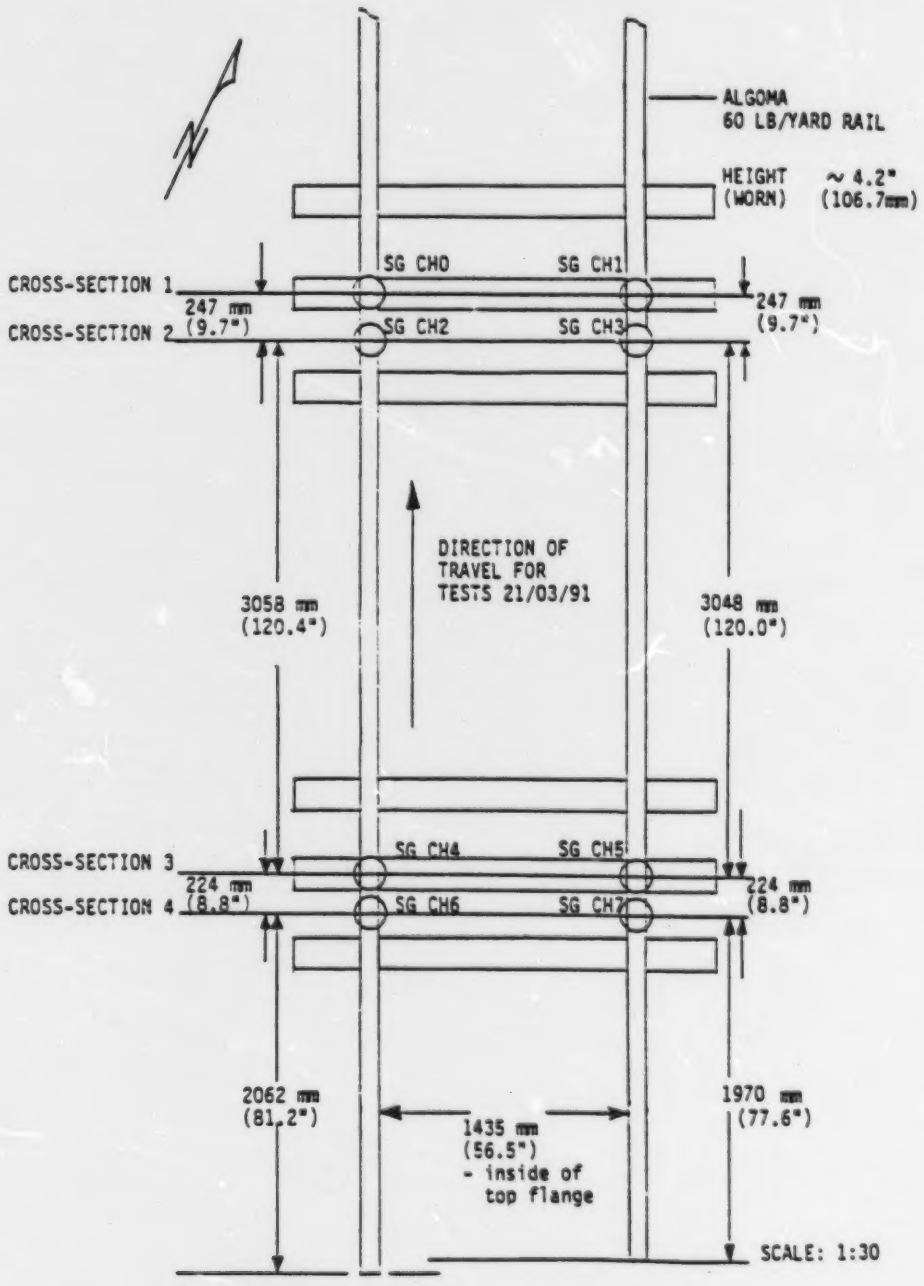


HIGH SPEED STRAIN GAUGE MEASUREMENT SYSTEM BLOCK DIAGRAM

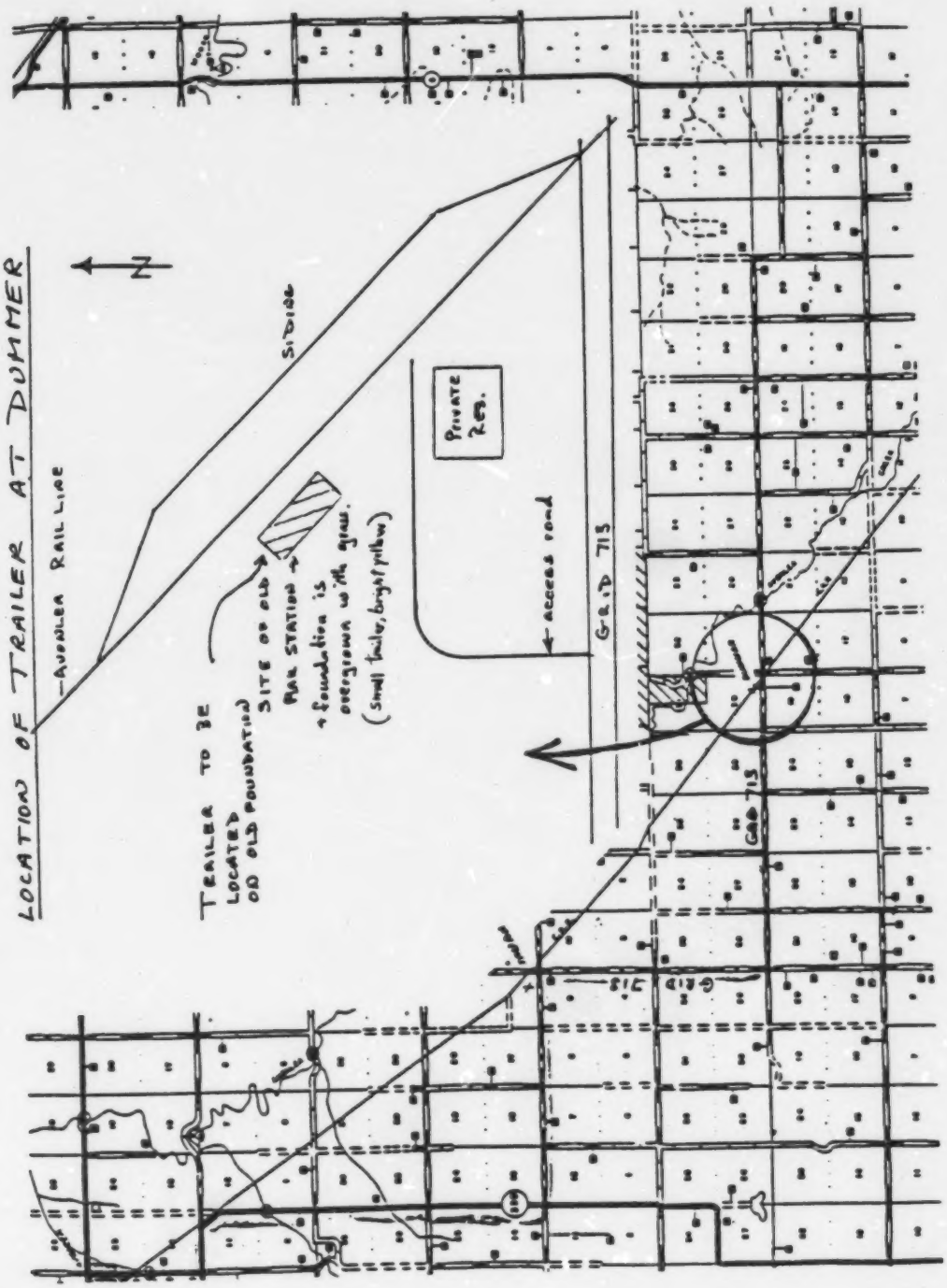
APPENDIX B

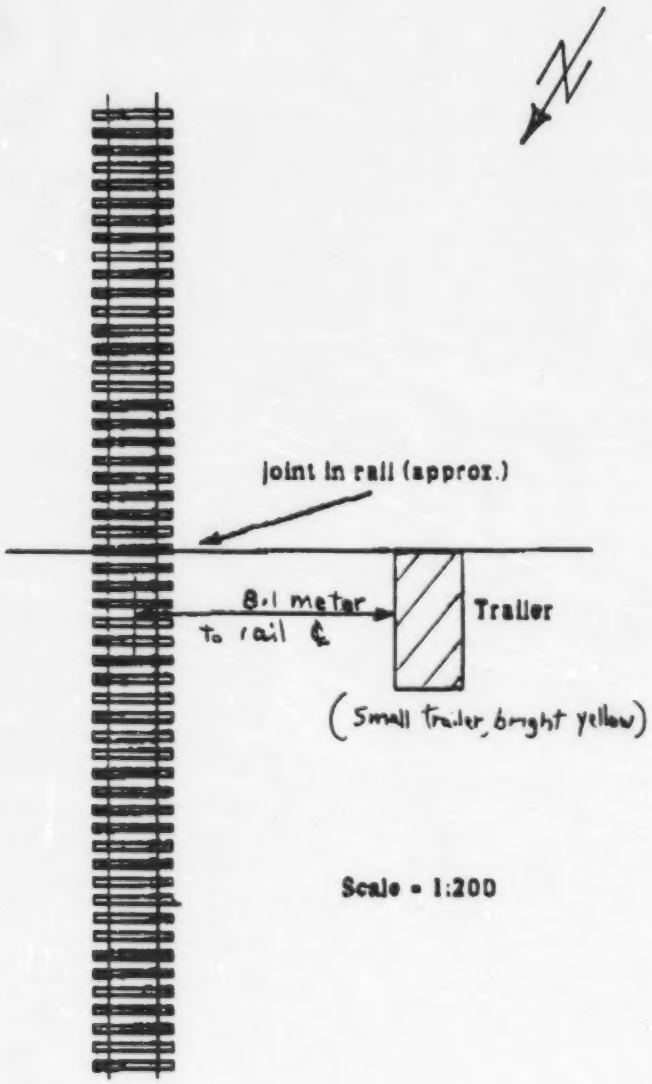
PLAN VIEW

STRAIN GAUGE LOCATIONS AT DRUMMER, SASKATCHEWAN



Strain gauge locations at the Dunmer, Saskatchewan test site on SRCL's Avonlea South Line.


LOCATION OF TRAILER AT DUNMER
N
AVONLEA RAIL LINE
SIDING
PRIVATE RES.
ACCESS ROAD
GRID 713
SITE OF OLD RAIL STATION + foundation is overgrown with grass. (small trailer, bricks/pillars)
TRAILER TO BE LOCATED ON OLD FOUNDATION



Sketch of Site at Dummer, Saskatchewan

APPENDIX C

SNAPSHOT DATA ANALYSIS SOFTWARE

Following is a screen plot of the main menu header for SNAPSHOP data analysis software used in this project. Also included is one example of a typical screen output of strain voltage response data using SNAPSHOT software. Note that all eight channels are displayed. The number of voltage points displayed in this plot are only a subset of the total number recorded during this test run. Eighty-five pages of plots were produced to examine the general trends of the strain voltage variations over the run time for each test. These plots are not included in this report. All plots, and others in various graphical formats as may be required can be printed from the recorded data on file.

Fluctuations in voltage signals correspond to the passing of train wheel axles. These voltage variations about the unstrained signal voltages for each channel correspond to loading and dynamic load reversal at each channel location on the test rails.

Main Menu Active

SNAPSHOT STORAGE SCOPE (TM) with SNAP-CALC

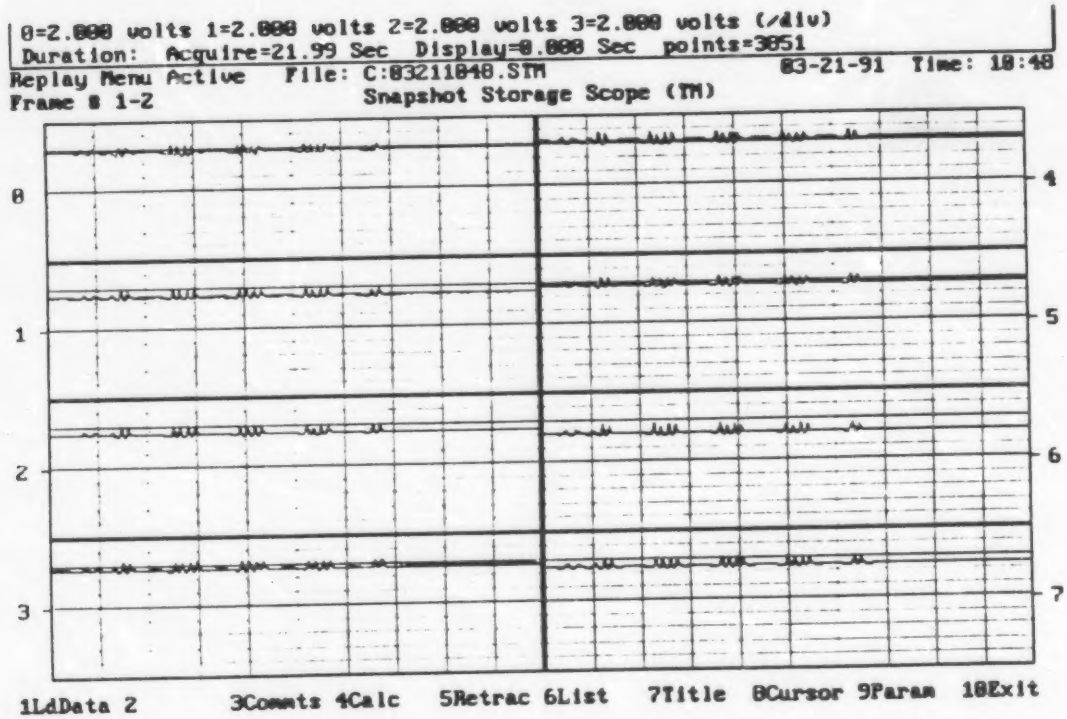
for RTI-800/815 & RTI-850/860 boards

Released May, 1990
Revision C

Feature	Version	Serial Number
SNAPSHOT STORAGE SCOPE	3.10a	AD200-03229
SNAP-CALC	3.00	
SNAP-STREAM	3.10	STR-03004

Copyright (c) 1985, 1986, 1987, 1988, 1989, 1990
HEM Data Corporation, All Rights Reserved

1Trace 2Replay 3 4Calc 5Setup 6 7Config 8 9Param 10Exit


0=2.000 volts 1=2.000 volts 2=2.000 volts 3=2.000 volts (/div)
Duration: Acquire=21.99 Sec Display=0.000 Sec points=3051
Replay Menu Active File: C:83211048.STM 03-21-91 Time: 10:48
Frame 8 1-2
Snapshot Storage Scope (TM)
0
1
2
3
4
5
6
7
1LdData 2 3Comnts 4Calc 5Retrac 6List 7Title 8Cursor 9Param 10Exit

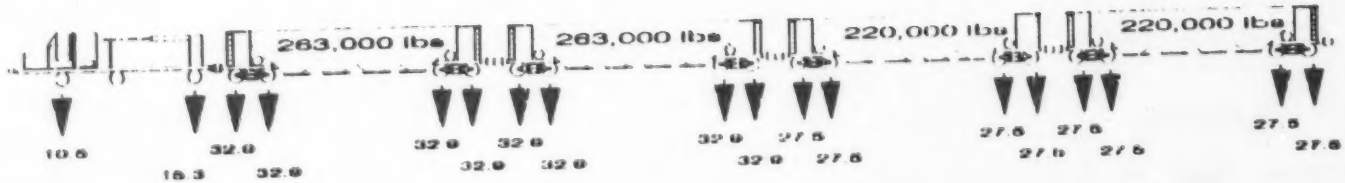
APPENDIX D

TEST TRAIN LAYOUT

TEST TRAIN LAYOUT

GVW including road/rail vehicle = 1,017,432 lbs.

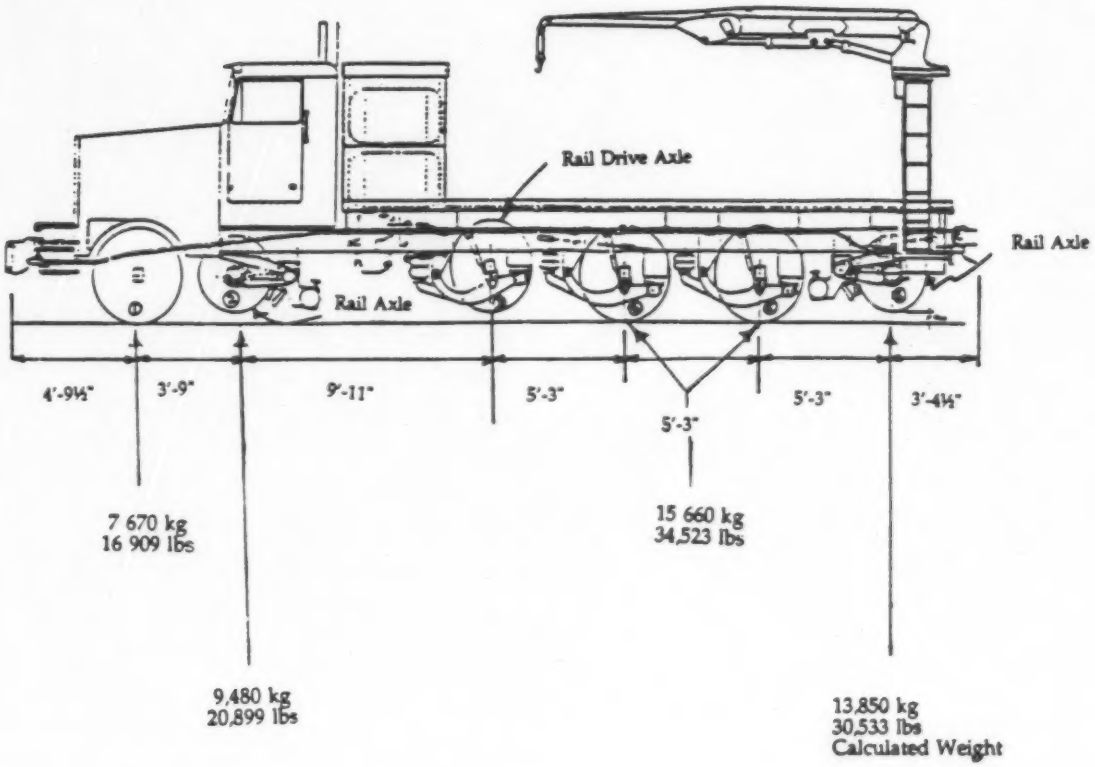
GVW (grain cars only) = 966,000 lbs.



NOTE: ALL AXLE REACTIONS SHOWN IN TONS

RAIL WHEEL DIAMETERS:

1. GRAIN CARS = 33" or 36" depending on car type
2. ROAD/RAILER = 33"



Tare Weight 23,330 kg
51,432 lbs

Approx. 150 lbs short of fuel
Driver in truck

Jan 11/91